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Improve the design of and assess upgrades to the Friction Stir welding system to reduce defects on surrogate unirradiated materials

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IMPROVE THE DESIGN OF AND ASSESS UPGRADES TO THE FRICTION STIR WELDING SYSTEM TO REDUCE DEFECTS ON SURROGATE UNIRRADIATED MATERIALS

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ACRONYMS

DOE	Department of Energy
EPRI	Electric Power Research Institute
FSW	Friction Stir Welding
LTO	Long-Term Operation
LWRS	Light Water Reactor Sustainability
NE	Office of Nuclear Energy
ORNL	Oak Ridge National Laboratory

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ABSTRACT

Friction stir welding of irradiated material in the 7930 hot cells at Oak Ridge National Laboratory was paused in 2020 after attempts to resolve the weld quality issues experienced in 2018-19. Plans have been developed but budget and manpower limitations have prevented further process development and evaluation of welding equipment as recommended in the 2020 milestone report. Advances in refractory tool materials in recent years may lead to superior results and are boron free. This report reviews the previous plan published in2020, recent research on friction stir welding of ferritic steel, austenitic steel, and nickel alloys to gain greater understanding to direct new process development. Multiple research reports lead to a conclusion that improper or incorrect thermal conditions may have caused the weld quality issues in 2018 unless an equipment issue is determined to be a main or contributing cause. Funding has not been available to implement the recommendations from the 2020 report and it is recommended that evaluation of welding equipment be conducted in parallel with process development.

This report also fulfills the FY 2021 LWRS milestone M3LW-21OR0406017, “Improve the design of and assess upgrades to the Friction Stir welding system to reduce defects on surrogate unirradiated materials”.

1. BACKGROUND

The hot cell welding cubicle completed installation in 2017 to allow the initial welding of ORNL irradiated coupons and has been detailed in several milestone reports [1,2]. Friction Stir Welding (FSW) encountered difficulty in producing high quality welds for the entire irradiated coupon length on nonirradiated and irradiated 304L coupons. Figures 1 and 2 show the issue that were encountered on nonirradiated and irradiated coupons with the surface and subservice defects for a large portion of the weld length on the coupons. The red arrows in figures 1 and 2 identifies the surface crack that occurred on one edge of the weld that extends a significant length along the weld. Figure 2 is a cross-section of the weld that further defines the subsurface defects or lack of bonding. In the bottom picture the top of the weld is at the bottom of the photo. The portion of the weld having satisfactory quality was sufficient to be metallurgically examined to determine if FSW is potentially applicable weld repair technique in a qualitative evaluation. The amount of acceptable weld length was insufficient to produce sufficient weld property test data for a future ASME code case to codify friction stir repair welding of irradiated reactor components. Further welding development was performed in a limited manner without success by increasing the plunge depth of the FSW tool at the beginning of the weld and at increments along the weld length with a goal of eliminating the surface defect for the entire weld length.

In 2020, it was recommended that FSW of irradiated coupons to be paused until the problem could be resolved [3]. This report further surmised that welding parameters being used were improper and a sufficient welding parameter envelope to produce defect free welds had not been adequately developed. It was acknowledged that other factors could be involved including equipment not operating properly, equipment not able to perform the programmed weld instructions, equipment misalignment, equipment damage or personnel programming issues may be contributing causes. The research and technical personnel reviewed data from welding development activities and other factors that created the surface and subsurface defects. A cause-and-effect fishbone diagram, figure 3, was developed to list the most likely factors causing the surface defect and to allow a methodical process of determining the root cause. A narrative associated with each contributor was included in the report (Table 1). Each person on the team ranked all items on the diagram as to likelihood of each item being a main cause, contributing cause or not likely to be a main or contributing cause. The report recommended two actions to resolve the weld quality issue and included further welding development efforts and an evaluation of the welding equipment if the redeveloped welding parameters also resulted in surface or subsurface defects.

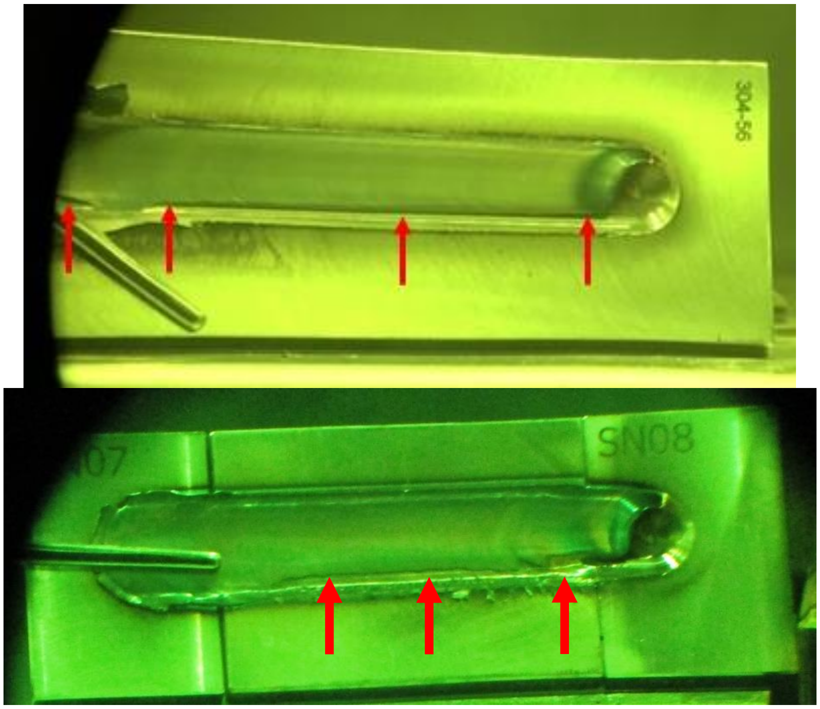

Figure 1. Excessive surface crack of FSW. Top: unirradiated SS304. Bottom: irradiated SS304.[3]

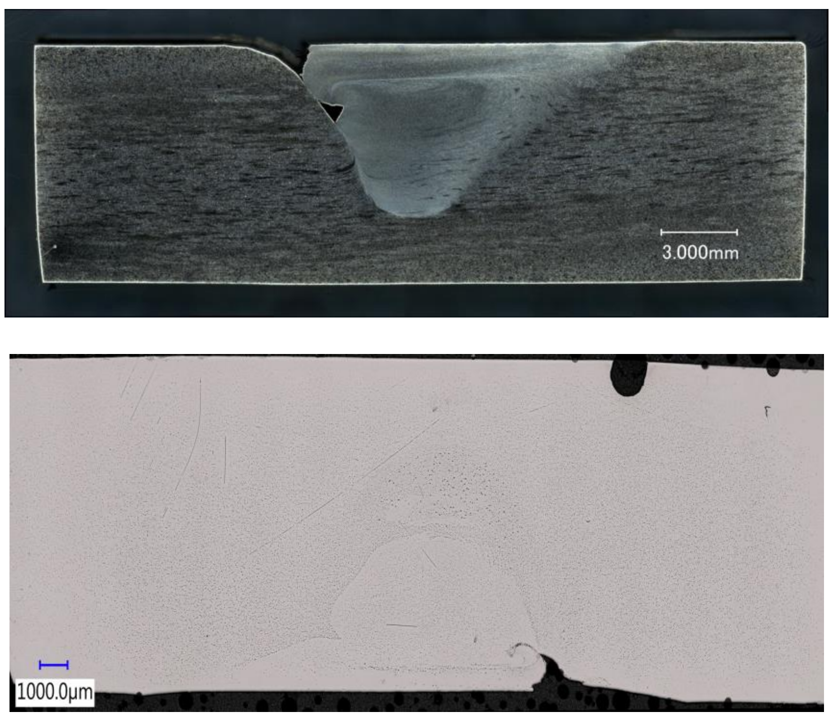

Figure 2. Cross-sectional view of FSW defects. Top: unirradiated SS304. Bottom: irradiated SS304 (top of weld at the bottom of photo).[3]

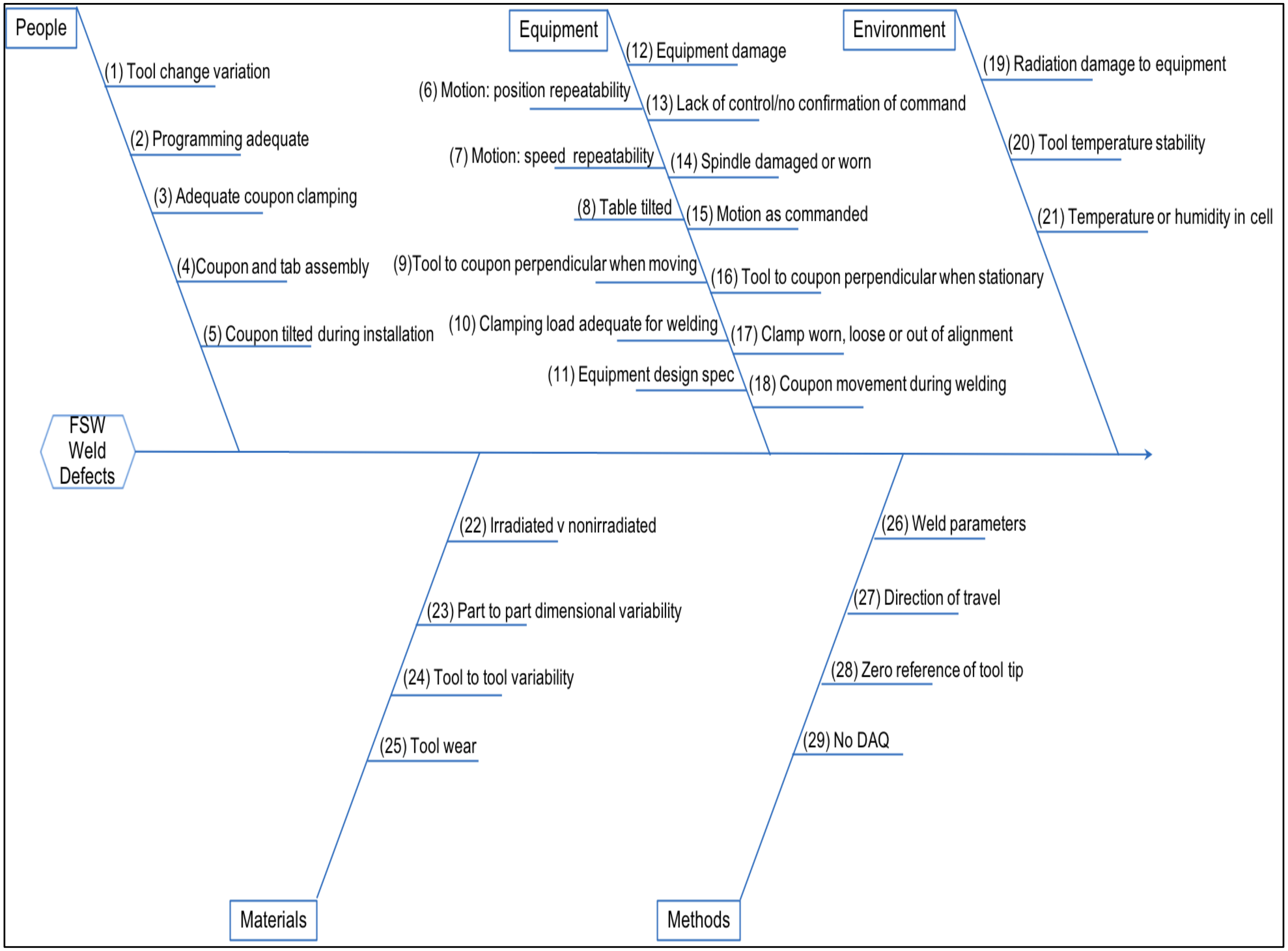

Figure 3. Cause and Effect Diagram [3]

Table 1. Description of Contributors to Weld Defects [3]

Contributor	Name	Group	Narrative
1	Tool change variation	Personnel	When FSW tools are changed is the operator fully seating the tool into the spindle?
2	Programming adequate	Personnel	Is the weld program used to control process adequate or insufficient?
3	Adequate coupon clamping	Personnel	Is the operator providing enough clamping on the vice to prevent coupon tilt or movement during welding?
4	Coupon and tab assembly	Personnel	Is the operator correctly assembling the coupon and start/stop tabs in a manner to prevent gaps or other issues that may affect weld quality?
5	Coupon tilted during installation	Personnel	Is the operator able to clamp the sample into the vice without the coupon becoming tilted?
6	Motion: distance repeatability	Equipment	Is the FSW able to perform motion repeatably from weld to weld. Are commands completed adequately under welding load?
7	Motion: speed repeatability	Equipment	Is the FSW table and spindle able to repeat the speed of motion from weld to weld while under load?
8	Table tilted	Equipment	Is the table tilted causing lack of tool engagement with coupon?
9	Perpendicular	Equipment	Does the tool maintain the intended angle with the coupon during welding?
10	Clamping Load	Equipment	Does the vice provide for sufficient clamping to resist welding loads on the coupon?
11	Design Spec	Equipment	Is the FSW design specification sufficient for the welds being performed or enough force or speed capability. Is the equipment capable?
12	Equipment Damage	Equipment	Is there mechanical or electrical damage to components that they can perform commanded actions. Have motors or amplifiers been damaged from motor stalling?
13	Lack of Control	Equipment	Is command executive and motor amplifiers communicating to accomplish program commands for speed or position while under welding loads? Do amplifiers provide sufficient electrical control or supply to perform functions under welding load?
14	Spindle	Equipment	Is there spindle damage to cause tool to rotate out of axis or wobble?

Contributor	Name	Group	Narrative
15	Motion Commanded	Equipment	Does the equipment successfully perform commanded functions?
16	Perpendicular	Equipment	Is the tool to coupon at the intended angle while stationary?
17	Clamp worn	Equipment	Is the vice loose, worn or out of alignment with table and or spindle?
18	Coupon movement	Equipment	Is the coupon moving during welding to cause loss of load or position and causing defects?
19	Rad damage	Environment	Has radiation degraded components that they do not function as intended. (i.e., motor encoders or tachometers?
20	Tool temperature	Environment	Is tool temperature steady during welding or changing from weld to weld?
21	Cell	Environment	Does temperature or humidity changes affect equipment operation or welding?
22	Irradiation	Materials	Is there a welding difference between irradiated and nonirradiated materials due to radiation hardening or strengthening?
23	Part variability	Materials	Are coupons have part to part dimensional variability that can cause welding issues?
24	Tool variability	Materials	Are critical tool features varying between tools?
25	Tool wear	Materials	Does tool wear affect the creation of weld defects or how many welds before tool is damaged?
26	Weld parameters	Methods	Are welding procedures have sufficient process window or are parameters at a cliff edge where small equipment changes cause weld defects?
27	Direction	Methods	Does welding direction affect weld defects or correct weld defects?
28	Zero reference	Methods	Is the zero reference between tool and coupon important to the process program?
29	DAQ	Methods	Does the lack of DAQ provide doubt in process commands are completed as programmed?

2. TECHNOLGY REVIEW

Friction stir welding of high temperature materials (i.e., ferritic steel, stainless steel, or nickel alloys) that are used in nuclear reactors continues to advance. The processing and tool materials have advanced in producing higher quality welds and reducing tool wear during welding. Several researchers have published findings to further define the classification, identification, and possible causes of FSW weld defects [4-10]. These references can be largely reduced to incorrect welding parameters producing unstable or incorrect thermal processing during FSW thusly producing defects. Additional causes of FSW weld defects are attributed to abnormal stirring conditions. Podrzj, et al, largely assigns the most common FSW weld defects to inappropriate welding parameters combinations of welding speed and tool rotation speeds [9]. In a report published in November 2020, Albannal discusses common defects in friction stir welding and includes examples of linear defects like what has been produced on non-irradiated and irradiated coupons in the ORNL hot cell [10]. This reference provides very useful information on the main cause and possible solutions for nine different types of FSW defects that can occur during friction stir welding. The welds produced in the welding cubicle contained two types of defects including surface and subsurface cracking or nonbonding defects.

3. FUTURE PLANS

The plans to correct and improve FSW of irradiated coupons remains essentially as recommended in the 2020 milestone report of further process development to develop appropriate welding parameter processing window to produce acceptable weld quality [3]. This would be performed on an existing friction stir welding equipment in a nonradioactive facility at ORNL. A part of the process development is evaluating the proper tool material as reactor repairs will receive additional irradiation. From the start of this program, it was known that tool materials were very important to further irradiation of weld repairs in nuclear reactors. It was known that the polycrystalline cubic boron nitride (PCBN) tool material selected for development efforts could be detrimental due to embedding boron into repair welds and an eventual replacement tool material would be needed. However, the availability of alternate tool materials was extremely limited. Recent research on alternate tool materials based on refractory metals are very promising and should be considered during future process development. It may be possible to evaluate table movements by image analysis. A trial was run in 2021 that indicates that this may be a potential evaluation tool. In addition, in 2022 it is planned to replace the laser welder wire feed system by personnel entry into the cubicle. At this time mechanical devices may be installed to evaluate the FSW welding equipment.

In a parallel effort, further investigations of the current FSW weld equipment to determine if equipment issues are the main cause or contributing cause for the surface and subsurface weld defects. A subset discussed earlier for evaluation are equipment not operating properly, equipment not able to perform the programmed weld instructions, equipment misalignment. These items are part of the information presented in figure 3 and table 1.

With these two efforts completed, welding of nonirradiated material to verify the parameter window and any equipment repairs or modifications may take place. If successful, it would be recommended to lift the 2020 pause and continue FSW processing of irradiated coupons.

4. SUMMARY

This report describes the status of the collaborative research between ORNL LWRS and EPRI LTO programs on Friction Stir Welding of irradiated materials. Friction stir welding of irradiated material in the 7930 hot cells at Oak Ridge National Laboratory was paused in 2020 after attempts to resolve the weld quality issues experienced in 2018-19. Plans have been developed but budget and manpower limitations have prevented further process development and evaluation of welding equipment as recommended in the 2020 milestone report.

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